

6-DOF MOTION EMULATION PLATFORM FOR LOW OVERHEAD APPLICATIONS: DESIGN AND VERIFICATION

Haru Tidmore ^{*}Benjamin Ingalls [†]Ali Hasnain Khowaja [‡] and Manoranjan Majji[§]

This paper presents the design and fabrication of a low-cost, mobile robotic platform to be used as a test bed for emulation of six Degree-of-Freedom (6DoF) systems. The emulation test-bed includes a Base Transport Vehicle (BTV) and a Canfield Joint. This modular system has been developed to combine the uninhibited motion of the BTV in the three planar degrees of freedom and the extended range of motion of the Canfield Joint for the remaining three out-of-plane degrees of freedom to satisfy the workspace requirements. Moreover, the design, construction, and modularity of the system make it an affordable and easily deployable motion emulation system compared to the previous platforms used at the Land Air and Space Robotics (LASR) Laboratory at Texas A&M University.¹ This test platform will provide valuable data for space based autonomy, proximity operation guidance and control, and a variety of other motion emulation experiments.

INTRODUCTION

Spacecraft operations pose significant challenges involving high cost, lengthy timelines, extensive guidelines, and high-risk scenarios that can potentially threaten existing systems in a similar orbit. Some of these operations may include: spacecraft manufacturing, assembly, clean-up, refueling, disposal, and inspection.² All of which pose complex concepts of operations that require extensive testing as a form of verification. By leveraging robotic emulation of space operations in a lab setting, system integration missions can be tested in a low risk and low-cost environment to verify and validate subsystems and mission requirements. At the Texas A&M LASR Lab, an existing system leveraging an omnidirectional base and a Stewart platform³ was used for space system demonstrations but has been outdated. This paper highlights the design and development of a cost-effective, modern, lightweight alternative to the original system that was limited in its applications due to its cost, weight, and age.

The new system is comprised of two key mechanical systems to achieve 6 Degrees of Freedom (DoF) motion: the Canfield Joint⁴ and the Base Transport Vehicle (BTV). The Canfield Joint is capable of pitch, roll, and vertical translation or heave control and is actuated by three motors. The BTV is an omnidirectional rover with three steered casters for holonomic motion. It is controlled by three DC motors and three continuous geared servo motors. One of the most significant benefits of this modular system is that the pitch, roll, and heave are de-coupled from x, y translational, and yaw. Computer Aided Designs (CADs) of both subsystems and their integration are shown in Figures 1 - 3. The kinematics and dynamics of each subsystem were modeled in Matlab⁵ and Simulink,⁶ and

^{*}Graduate Assistant, Texas A&M University

[†]Graduate Assistant, Texas A&M University

[‡]Graduate Assistant, Texas A&M University

[§]Professor, Texas A&M University

ViconTM provided inertial position and orientation feedback. The code base for the system was developed with ROS2 to allow for quick and easy integration into any research environment.

As shown in Figure 2, the Canfield Joint is comprised of three legs and a top base plate as the end effector. The motivation behind using this joint is its high maneuverability and expressive workspace. There are a total of 15 joint angles, and the system is highly nonlinear. Still, it can be simplified using a geometric approach, which was used to develop the inverse kinematic mapping between the roll, pitch, and heave to base joint angles.

The base transport vehicle, as shown in Figure 1, leverages caster dynamics and controlled caster yaw to achieve holonomic planar motion. That being, having uncoupled planar translation and yaw control. A digital control scheme is being developed to provide smooth motion for emulation.

The overview and additional detail of each subsystem is as follows: Section II discusses the design decisions of each system. Section III serves as a discussion on the control design as. Section IV outlines the canonical cases and results of the system. Section V presents the conclusion, and future work of the system.

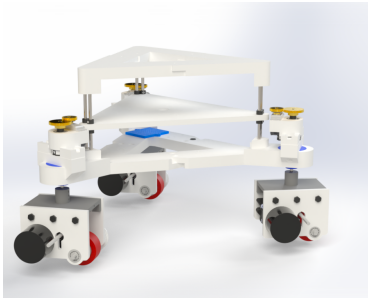


Figure 1: Base Transport Vehicle

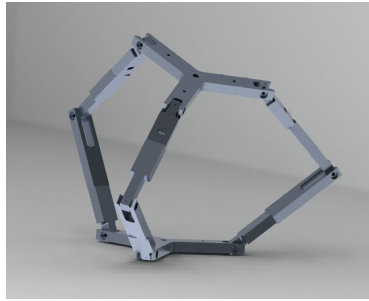


Figure 2: Canfield Joint



Figure 3: CHOMER

DESIGN OF SYSTEM

An early design decision that was made was to decouple the planar and out-of-plane degrees of freedom. This decision was driven largely on the previous model of HOMER¹ and the workspace requirements being infinite in the planar degrees of freedom. Decoupling these broke the system into two subsystems: the BTV, which provides the planar degrees of freedom, and the Canfield Joint, which provides the out-of-plane motion. The design and development of both subsystems will be explored in depth. Canfield Holonomic Omni-directional Motion Emulation Robot (CHOMER) was designed to leverage modular and iterative design techniques in order to emulate complex and expensive dynamics operations. Be it in space or sea applications; the idea was to have a system that has a large, robust workspace while also keeping costs down in a compact form factor for in-lab testing operations.

Canfield Joint Qualitative Analysis

The trade space of a modular 3+ DoF mechanisms included a Stewart platform, Canfield Joint, robotic manipulators, and spherical wrists. The first requirement of the pointing and actuating mechanism was that it needed to have freedom in Roll, Pitch, and Z-translational. Thus eliminating spherical wrists. The second requirement is platform availability and integrated modularity, in other

words, the ability to put additional subsystems on top. While robotic arms are widely available and well-understood, their ability to hold large volumetric payloads that require a significant amount of surface area for stability makes them unacceptable. Thus, leaving a Stewart platform and the Canfield Joint. A previous system at the LASR lab was used, known as HOMER,¹ which had an omnidirectional base and a Stewart platform. Due to the size, weight, and maintenance cost of the system, a newer, more modern approach was desired. Some basic requirements were derived for generalized sea and space emulation applications. The system shall carry 2 to 15 lbs of payload. The system shall pitch and roll at least 40 degrees. The system shall heave at least 6 inches. With these requirements, the canfield base plates and arms can be sized.

Base Transport Vehicle Qualitative Analysis

The design goals of the BTV were to create an accurate and smooth holonomic emulation platform for the planar degrees of freedom with a low overhead requirement. The workspace of these degrees of freedom were to be practically infinite, limited only by the constraints of the testing venue. Due to this desire for a large workspace and low overhead, a float craft was ruled out as prohibitively costly. The BTV sought to maximize maneuverability, portability, and precision while minimizing cost and complexity. With this in mind, Differential Drive, Tricycle, Ackermann, Mecanum, and Swerve Drive vehicles were considered. Although the differential drive offers a straightforward and cost-effective design, its lack of stability and expressiveness in a 3 DoF workspace brought on the need for an extra wheel. The tricycle offered geometric simplicity, but its lack of maneuverability in turning applications limited its ability to be an accurate emulation system. Ackermann was dropped because of its inability to decouple yaw from translation. Mecanum vehicles are very versatile and have zero turning radii, but have very low traction, and as a result, the precision and accuracy of this type of vehicle were questioned. Therefore, the Swerve Drive vehicle, where each wheel is steered and driven, was chosen. We sought to take advantage of advantage of the geometric simplicity of the tricycle configuration and steer all three driven wheels. This allows for smooth control and uncoupled maneuverability in the planar degrees of freedom.

System Modeling and Motion Analysis

The Canfield Joint and the BTV were analyzed kinematically and dynamically with iterative and analytical methods in Matlab, Simulink, and Python.

Canfield Joint Using Matlab and Simulink, the Canfield Joint could be dynamically modeled with force and torque inputs without defining the plant itself through equations of motion. This served as a first-level motion analysis to intuitively understand the joint's coupled kinematics. With this low-fidelity model, a torque-controlled closed-loop PID controller was designed to control the Roll-Pitch-Heave of the end effector. The closed loop spatial chain's mass properties and kinematic constraints were modeled using Solidworks⁷ and exported into Simulink using Simscape Multibody.⁸ Using torque control of the three base arms, the physical workspace of the Canfield Joint was evaluated, and validated the motor sizing for specified payload masses. The most significant contribution of the Simulink model is the ability to provide base angles or torques and visualize the resulting pose, shown in Figure 4. The preliminary control law designed in Simulink

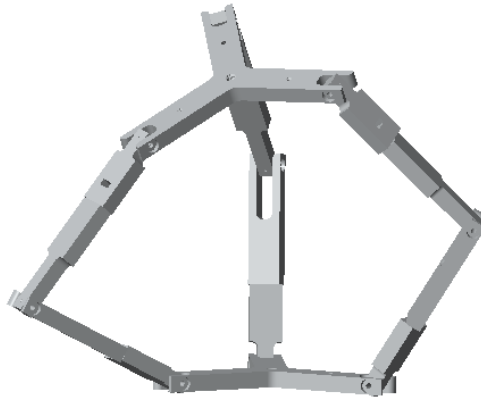


Figure 4: Simulink Model

showed promising but not robust control. In addition, the iterative and nondeterministic nature of the Simulink model posed problems for physical integration and testing.

Using the results published by Bueno⁹ the kinematics of the Canfield Joint can be modeled using a series of geometric relationships and assumptions. The key assumption that simplifies the Canfield Joint's coupled kinematic chains is that the plane that contains all three mid-joints, denoted by M , is a plane of symmetry between the base plate and end-effector (distal plate). The symmetric plane assumption allows the kinematics to be solely determined by the locations of the mid-joint locations, which are easily calculated using elementary trigonometry, shown in Figure 5.

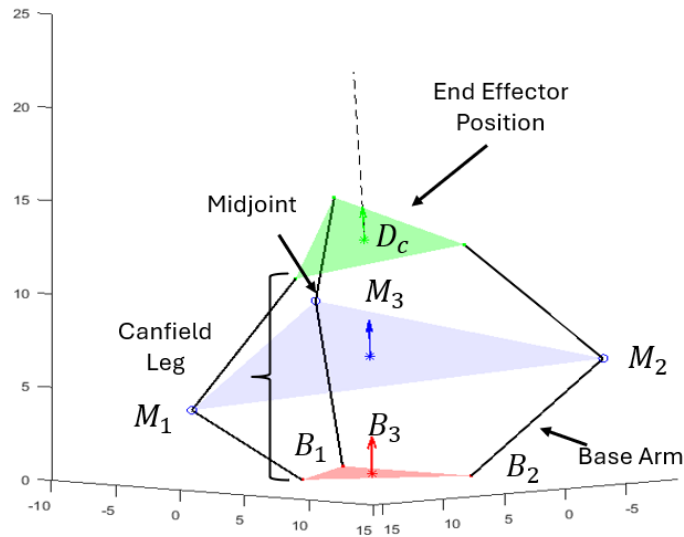


Figure 5: Canfield Joint Parameters and Vocabulary

Furthermore, the inverse kinematics are defined through the specification of the end effector center (desired position for the distal center), affine pointing (end effector is directed at a desired

point), or roll/pitch pointing (end effector is required to point in a certain direction). Each method has advantages or disadvantages for various applications, but specifying the end-effector's center is sufficient for the emulation of 6 DoF motion. This results in a forward and inverse relationship of base angles to end-effector X-Y-Z position in space. The implementation of the equations is as follows; Using an inertial cartesian coordinate system at the origin of the base plate.

$$\varepsilon = [O, \hat{e}_1, \hat{e}_2, \hat{e}_3] \quad (1)$$

Defining the location of each of the base joint locations and producing the base plane.

$$B_1 = \frac{b}{\sqrt{3}}\hat{e}_1, B_2 = R_3\left(\frac{\pi}{3}\right) B_1, B_3 = R_3\left(\frac{\pi}{3}\right) B_2 \quad (2)$$

Such that R_3 is a passive rotation matrix about the inertial $\hat{k}$ axis. Continuing to the mid joints as a function of the base arm angles to develop the forward kinematic equations such that $\theta_1, \theta_2, \theta_3$ are the angles between the vector $B_i\vec{M}_i$ and the plane base plane. The mid points can be defined as such:

$$\mathbf{m}_1 = \left(l \cos(\theta_1) + \frac{b}{\sqrt{3}}, 0, l \sin(\theta_1) \right) \quad (3)$$

$$\mathbf{m}_2 = \left(\frac{-l}{2} \cos(\theta_2) - \frac{b}{2\sqrt{3}}, l \frac{\sqrt{3}}{2} \cos(\theta_2) + \frac{b}{2}, l \sin(\theta_2) \right) \quad (4)$$

$$\mathbf{m}_3 = \left(\frac{-l}{2} \cos(\theta_3) - \frac{b}{2\sqrt{3}}, \frac{-l\sqrt{3}}{2} \cos(\theta_3) - \frac{b}{2}, l \sin(\theta_3) \right) \quad (5)$$

Such that l is the half length of the leg, defined in Figure 5. With the midpoints the midplane, centroid, and normal vector of the midplane are defined as such.

$$\mathbf{N} = (\mathbf{m}_2 - \mathbf{m}_1) \times (\mathbf{m}_3 - \mathbf{m}_1) \quad (6)$$

$$\mathbf{N}_c = \frac{1}{3}(\mathbf{m}_1 + \mathbf{m}_2 + \mathbf{m}_3) \quad (7)$$

Due to the symmetry of the Canfield Joint, the distal plate must be a reflection of the base plate across the midplane. Where the following equation is the reflection of point a across plane P which is defined with point q and normal vector $\mathbf{N}$.

$$\mathbf{R}_p = \mathbf{a} - 2 \frac{\mathbf{N} \cdot (\mathbf{a} - \mathbf{q})}{\|\mathbf{N}\|^2} \mathbf{N} \quad (8)$$

In application, point q is the point on the symmetric plane reflecting point a . As defined in Figure 5, the B_i points are substituted for a , and the M_i points are substituted for q , which yield the distal plates vertices D_i . These forward kinematic equations are useful for validating the intuition developed in the numerical Simulink model.

The inverse kinematics of the Canfield Joint allow for the calculation of required base arm angles for a desired end effector X-Y-Z position in inertial space. The method is outlined in Bueno et. al.⁹ and attempts to determine a plane P that intersects with each midcircle (circle containing the

corresponding ith base, midjoint, and distal position). In other words if P is given by $\hat{N} \cdot (\mathbf{x} - \mathbf{q}) = 0$ then we must find the midjoint that satisfies the following equations

$$\begin{aligned} \mathbf{N} \cdot (\mathbf{m}_i - \mathbf{q}) &= 0, \\ \hat{\mathbf{N}}_i \cdot (\mathbf{m}_i - \mathbf{B}_i) &= 0, \\ \|\mathbf{m}_i - \mathbf{B}_i\|^2 &= l_i^2 \end{aligned}$$

that is, the midjoint must be contained in the midcircle and midplane, and separated from the base joint by the length of the leg (l_i). The following equations are written in terms of the ith joint without any loss in generality. Given an end-effector position $\mathbf{D}_c$ we can find a point on the midplane center to be $1/2\mathbf{D}_c$. Begin by finding a point which is contained in both the midcircle and midplane. One can do this using a constrained optimization with Lagrange Multipliers developed by John Krumm.¹⁰ The optimization problem is given by the cost function

$$J = \|\mathbf{q}_i - \mathbf{m}_0\|^2 \quad (9)$$

subject to the constraints

$$(\mathbf{q}_i - \mathbf{B}_i) \cdot \mathbf{M}_i = 0 \quad (10)$$

$$(\mathbf{q}_i - \frac{1}{2}\mathbf{D}_c) \cdot \mathbf{D}_c = 0 \quad (11)$$

where $\mathbf{m}_0$ serves as the closest point, $\mathbf{q}_i$ is the solution to the optimization problem, and $\mathbf{M}_i$ is the normal vector of the i -th midcircle. The objective function along with the two constraints can be modeled as a Lagrange multiplier problem

$$w = \|\mathbf{q}_i - \mathbf{m}_0\|^2 + \lambda_1(\mathbf{q}_i - \mathbf{B}_i) \cdot \mathbf{M}_i + \lambda_2(\mathbf{q}_i - \frac{1}{2}\mathbf{D}_c) \cdot \mathbf{D}_c \quad (12)$$

where λ_1 and λ_2 are the lagrange multipliers. After taking the necessary partial derivatives we are left with the following system of equations

$$A_i \mathbf{q}_i = \mathbf{z}_i \quad (13)$$

$$A_i = \begin{bmatrix} 2 & 0 & 0 & M_{ix} & D_{cx} \\ 0 & 2 & 0 & M_{iy} & D_{cy} \\ 0 & 0 & 2 & M_{iz} & D_{cz} \\ M_{ix} & M_{iy} & M_{iz} & 0 & 0 \\ D_{cx} & D_{cy} & D_{cz} & 0 & 0 \end{bmatrix}$$

$$\mathbf{z}_i = [B_{ix} \quad B_{iy} \quad B_{iz} \quad \mathbf{B}_i \cdot \mathbf{M}_i \quad \frac{1}{2}\mathbf{D}_c \cdot \mathbf{D}_c]^T \quad (14)$$

$$\mathbf{q}_i = [q_{1x} \quad q_{2x} \quad q_{3x} \quad \lambda_1 \quad \lambda_2]^T \quad (15)$$

We are only interested in the first three components of the $\mathbf{q}_i$ vector, furthermore the two Lagrange multiplier terms will be dropped from $\mathbf{q}_i$ in the following equations. Once $\mathbf{q}_i$ is obtained, we obtain the corresponding midjoint using the following equations

$$\nu_i = \frac{\mathbf{D}_c \times \mathbf{M}_i}{\|\mathbf{D}_c \times \mathbf{N}_i\|} \quad (16)$$

$$\delta_i = q_i - B_i \quad (17)$$

$$\Delta_i = (\nu_i \cdot \delta_i)^2 - (||\delta_i||^2 - l^2) \quad (18)$$

$$m_i = q_i - (\nu_i \cdot \delta_i \pm \sqrt{\Delta_i})\nu_i \quad (19)$$

It is important to note that the final equation gives two possible locations for m_i , therefore it is up to the engineer to determine which point is feasible for their configuration. The method employed in this paper is to choose the angle contained between 0 and 90 degrees. The base angle can be found via

$$\theta_i = \arctan 2 \left(m_{i,z}, m_{1,x} - \frac{b}{\sqrt{3}} \right) \quad (20)$$

where arctan2 is written to denote quadrant specificity.

Base Transport Vehicle The BTV uses the dynamics of the caster wheels to produce any desired instantaneous velocity and rotation in the planar degrees of freedom. The ability to smoothly and accurately produce this motion is a key component of the success of the project. To accomplish this, a multi layered control was used. Using digital control methods, a system will be developed to allow for successful execution of both pre-planned and actively controlled motion.

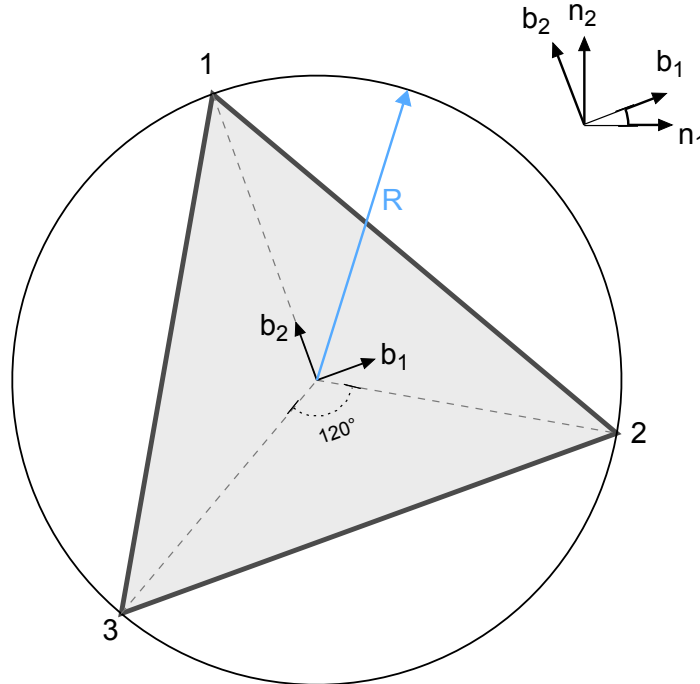


Figure 6: Body Reference Frame of BTV

Let the system be modeled as an equilateral triangle of radius R . The inertial frame is $N = \{O, \hat{n}_1, \hat{n}_2, \hat{n}_3\}$. The Body fixed frame is $B = \{O, \hat{b}_1, \hat{b}_2, \hat{b}_3\}$ with;

$$\omega^{B/N} = \dot{\theta} \hat{n}_3 \quad (21)$$

The center of the triangle is at point (x, y) with rotation θ relative to N

The positions and velocities of each corner of the triangle can be expressed as,

$$\vec{r}_1 = R\hat{b}_2 + x\hat{n}_1 + y\hat{n}_2 \quad (22)$$

$$\vec{r}_2 = \frac{\sqrt{3}}{2}R\hat{b}_1 - \frac{R}{2}\hat{b}_2 + x\hat{n}_1 + y\hat{n}_2 \quad (23)$$

$$\vec{r}_3 = -\frac{\sqrt{3}}{2}R\hat{b}_1 - \frac{R}{2}\hat{b}_2 + x\hat{n}_1 + y\hat{n}_2 \quad (24)$$

Time derivatives of the position vectors:

$$\dot{\vec{r}}_1 = -\dot{\theta}R\hat{b}_1 + \dot{x}\hat{n}_1 + \dot{y}\hat{n}_2 \quad (25)$$

$$\dot{\vec{r}}_2 = \dot{\theta}\frac{\sqrt{3}}{2}R\hat{b}_2 + \dot{\theta}\frac{R}{2}\hat{b}_1 + \dot{x}\hat{n}_1 + \dot{y}\hat{n}_2 \quad (26)$$

$$\dot{\vec{r}}_3 = -\dot{\theta}\frac{\sqrt{3}}{2}R\hat{b}_2 + \dot{\theta}\frac{R}{2}\hat{b}_1 + \dot{x}\hat{n}_1 + \dot{y}\hat{n}_2 \quad (27)$$

Given a commanded $\dot{x}$, $\dot{y}$, and $\dot{\theta}$, the appropriate $\dot{\vec{r}}_1$, $\dot{\vec{r}}_2$, and $\dot{\vec{r}}_3$ can be found. To map this to control inputs, one must take into account the dynamics of the caster wheels. To do this, first express $\dot{\vec{r}}_i$ in the B frame using:

$$\hat{n}_1 = \cos \theta \hat{b}_1 + \sin \theta \hat{b}_2 \quad (28)$$

$$\hat{n}_2 = \cos \theta \hat{b}_2 - \sin \theta \hat{b}_1 \quad (29)$$

$$\dot{\vec{r}}_1 = (\dot{x} \cos \theta + \dot{y} \sin \theta - \dot{\theta}R)\hat{b}_1 + (\dot{y} \cos \theta - \dot{x} \sin \theta)\hat{b}_2 \quad (30)$$

$$\dot{\vec{r}}_2 = (\dot{x} \cos \theta + \dot{y} \sin \theta + \dot{\theta}\frac{R}{2})\hat{b}_1 + (\dot{y} \cos \theta - \dot{x} \sin \theta + \dot{\theta}\frac{\sqrt{3}}{2}R)\hat{b}_2 \quad (31)$$

$$\dot{\vec{r}}_3 = (\dot{x} \cos \theta + \dot{y} \sin \theta - \dot{\theta}\frac{R}{2})\hat{b}_1 + (\dot{y} \cos \theta - \dot{x} \sin \theta + \dot{\theta}\frac{\sqrt{3}}{2}R)\hat{b}_2 \quad (32)$$

For a caster wheel of length ℓ , the velocity of its pivot point is given by

$$\dot{\vec{r}} = V\hat{c}_1 + \dot{\psi}\ell\hat{c}_2 = (V \cos \psi - \dot{\psi}\ell \sin \psi)\hat{b}_1 + (V \sin \psi + \dot{\psi}\ell \cos \psi)\hat{b}_2 \quad (33)$$

$$\omega^{C/B} = \dot{\psi}\hat{b}_3 \quad (34)$$

Assuming a knife edge constraint, V_1 is the forward velocity produced by the wheel and $\dot{\psi}$ is the angular velocity around the pivot. The frame $C = \{O, \hat{c}_1, \hat{c}_2, \hat{c}_3\}$ is fixed to the caster.

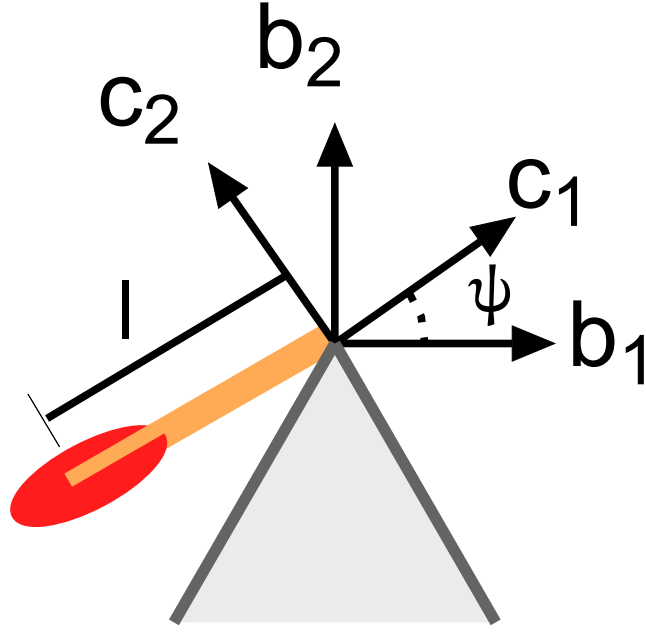


Figure 7: Caster Reference Frame wrt BTM

If some generic velocity (α, β) is desired, the appropriate commands are given by;

$$\dot{\vec{r}} = \alpha \hat{b}_1 + \beta \hat{b}_2 \quad (35)$$

$$V = \alpha \cos \psi + \beta \sin \psi \quad (36)$$

$$\dot{\psi} = \frac{\beta \cos \psi - \alpha \sin \psi}{\ell} \quad (37)$$

Plugging our previous equations in for α and β this the mapping from $\dot{x}$, $\dot{y}$, and $\dot{\theta}$ to the control inputs is;

$$V_1 = (\dot{x} \cos \theta + \dot{y} \sin \theta - \dot{\theta} R) \cos \psi_1 + (\dot{y} \cos \theta - \dot{x} \sin \theta) \sin \psi_1 \quad (38)$$

$$\dot{\psi}_1 = \frac{(\dot{y} \cos \theta - \dot{x} \sin \theta) \cos \psi_1 - (\dot{x} \cos \theta + \dot{y} \sin \theta - \dot{\theta} R) \sin \psi_1}{\ell} \quad (39)$$

$$V_2 = (\dot{x} \cos \theta + \dot{y} \sin \theta + \dot{\theta} \frac{R}{2}) \cos \psi_2 + (\dot{y} \cos \theta - \dot{x} \sin \theta + \dot{\theta} \frac{\sqrt{3}}{2} R) \sin \psi_2 \quad (40)$$

$$\dot{\psi}_2 = \frac{(\dot{y} \cos \theta - \dot{x} \sin \theta + \dot{\theta} \frac{\sqrt{3}}{2} R) \cos \psi_2 - (\dot{x} \cos \theta + \dot{y} \sin \theta + \dot{\theta} \frac{R}{2}) \sin \psi_2}{\ell} \quad (41)$$

$$V_3 = (\dot{x} \cos \theta + \dot{y} \sin \theta - \dot{\theta} \frac{R}{2}) \cos \psi_3 + (\dot{y} \cos \theta - \dot{x} \sin \theta + \dot{\theta} \frac{\sqrt{3}}{2} R) \sin \psi_3 \quad (42)$$

$$\dot{\psi}_3 = \frac{(\dot{y} \cos \theta - \dot{x} \sin \theta + \dot{\theta} \frac{\sqrt{3}}{2} R) \cos \psi_3 - (\dot{x} \cos \theta + \dot{y} \sin \theta - \dot{\theta} \frac{R}{2}) \sin \psi_3}{\ell} \quad (43)$$

Hardware and Physical Prototyping

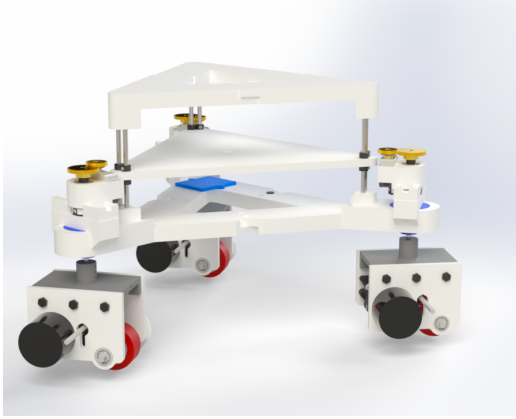


Figure 8: BTV CAD

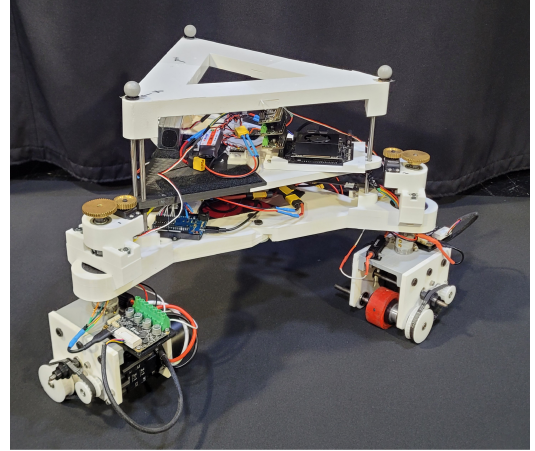


Figure 9: Prototype of BTV

Base Transport Vehicle Each caster on the BTV is driven by a Rev Robotics NEO Brushless Motor V1.1 controlled by an ODrive S1 brushless motor control board. This motor has a 9 to 1 gear box and a 2 to 1 reduction from the timing belt to give an 18 to 1 speed reduction. This is the V_i input. Feedback for the drive motors is provided by internal hall effect encoders in the NEO motors. Power and serial data is passed to the caster through a slip-ring. The caster angle is controlled by an Adafruit continuous servo with a 2 to 1 speed reduction. This is the ψ_i input. Feedback for the caster angle is given by CUI AMT10E2-V capacitive encoders with index pulses set to 500 CPR. The encoders are driven by a Arduino Leonardo micro controller board.

Canfield Joint The motors controlling the base arms of the Canfield Joint are Perfect Pass high torque servos connected to the arm via a 4-bar linkage assembly, shown in 10.

The kinematic constraint equations for the closed-loop 4-bar are as follows.

$$x : a \cos(\theta) + b \cos(\beta) - c \cos(\phi) - d = 0 \quad (44)$$

$$y : a \sin(\theta) - b \sin(\beta) - c \sin(\phi) = 0 \quad (45)$$

The base joint angle of the canfield joint is represented as θ shown in 11. The angle ϕ is rigidly attached to the servo horn. The ratio of length a to c is 3:1, which gives a 3 times mechanical advantage of the servo's rated torque at 7.4 volts.

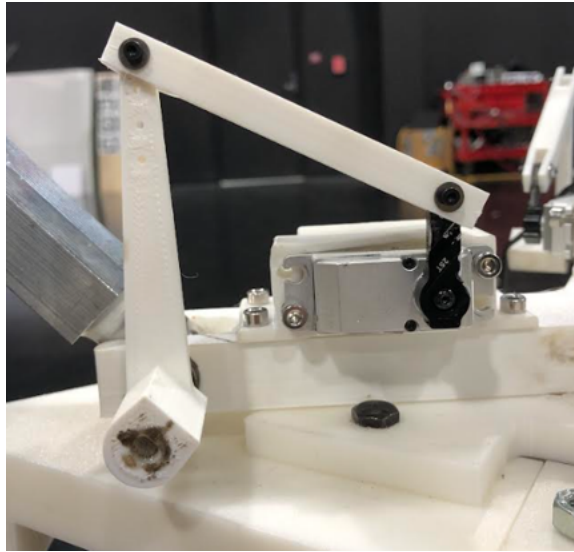


Figure 10: Servo 4 bar linkage assembly to the canfield base

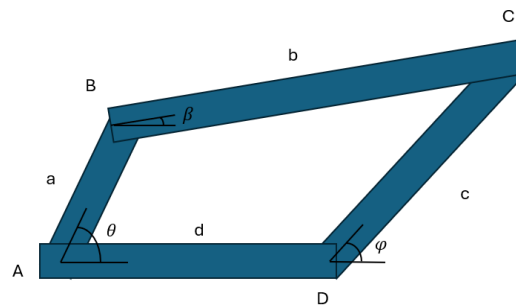


Figure 11: 4-Bar Closed loop mechanism

Computational Hardware

The Computational element of the CHOMER System is a Jetson Nano Orin Developer Kit with a SSD hard-drive added to increase performance. It communicates over a serial USB connection to the ODive motor control boards and the Arduino. An Adafruit servo control bonnet controls the servos in the Canfield joint and the casters. All electronics are powered by onboard LiPo batteries.

CONTROL DESIGN

The software design of the CHOMER system used a ROS2 framework to help with modular development and ease of implementation in other labs. Global position feedback was provided by a Vicon Motion Capture System. However, since this is its own ROS2 node, it can be switched out for an IMU or some other pose estimation method without major changes to the software suite.

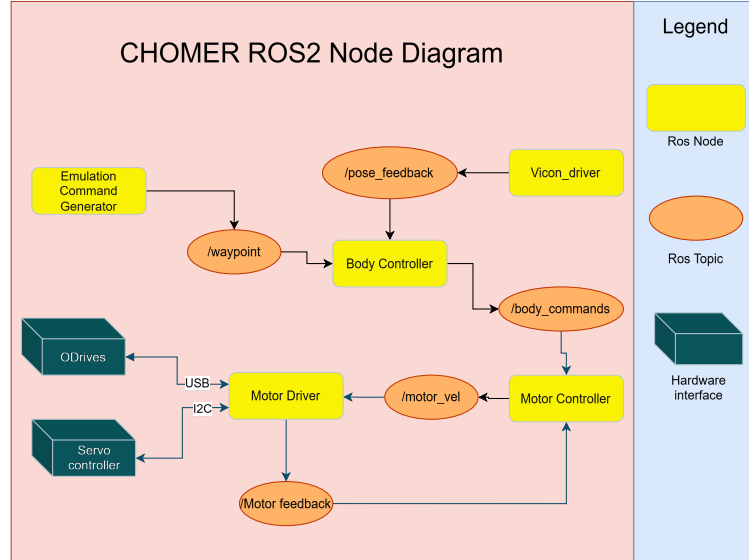


Figure 12: CHOMER ROS2 Node Diagram

Base Transport Vehicle

The BTV uses a nested control design, namely a PID controller on the ODrive boards to control motor velocity, a body velocity to motor velocity controller, and a waypoint tracking controller. The waypoint tracking controller, housed in the ROS Body controller node, takes a commanded 6-DOF waypoint from the topic `/waypoint`, and publishes a commanded 6-DOF body velocity to the topic `/body_vels` with feedback from `/pose_feedback`. The Motor Controller node takes the commanded body velocity and maps that to commanded motor velocities using equations 38-43. Finally, the motor driver node sends the velocities to the Odrive motor controller boards. These boards contain a digital PID controller with customizable gains. A similar setup is in the motor driver node to control the caster angle servos.

Canfield Joint

With the inverse kinematics, the X-Y-Z position of the end effector can be found in closed form yielding efficient control in a nominal environment. Two validations campaigns for the proposed inverse kinematics model demonstrated that the model accurately controls all three out of plane degrees of freedoms sufficient for emulation. The first validation campaign was done with the previously developed Simulink model, which leveraged Simulink purely as a visualizer and data acquisition model. In order to fairly compare different control laws, and developments of the Canfield Joint two canonical cases were used to demonstrate success. One is tracking a 2-inch circle in

X-Y-Z space, and the second is a predetermined series of roll and pitch angles at different heights. The following figure demonstrates the simulated Canfield Joint following the circle canonical case. Using the inverse kinematics integrated into Simulink, a nominal predicted trajectory is shown in Figure 13 at the top in light blue.

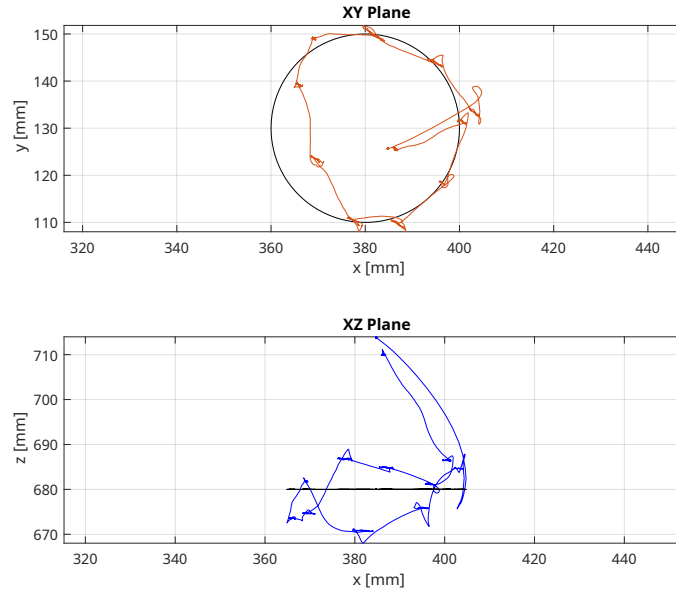


Figure 13: Open-loop control of physical prototype canonical case results. The top figure shows the XY position in space, the black line is the nominal trajectory, and the orange and blue are the sensed position. Starting from an initial height at zero relative displacement from the base. The bottom figure shows the heave or height of the base; this canonical case demonstrates a circle at a constant height.

In reference to Figure 13. The imperfections in the motion tracking were found to be equal contributions on different scales of two things. First, the mechanical slop of working with 3-D printed parts in the prototyping stage. This led to various issues stemming from inelastic deformation of the loaded joints at fastening points. This led to a biased performance that can easily be quantified as a linear performance degradation throughout the workspace. For example, if the waypoint was set to 1 meter, in the presence of slop the waypoint would reach .85 meter. Another effect that was only present at the bounds of the heave workspace while pitching and rolling is a nonlinear progression of the base angles. This is due to a 4-bar connection of the Servo motor to the base canfield arms, shown in Figure 10. The 4-bar effect is overcome by solving for the input and output angles to characterize the nonlinearity of the linkage workspace.

In Simulink, mechanical slop was modeled by adding a constant angle to the inputted base angles.

$$\Delta\theta_i = \theta_i + \delta_i$$

Now with the error modeled in Simulink a control algorithm can be simulated and tested prior to implementation. This also serves as a key feature for future work, in the event of new control architectures needing to be tested prior to implementation. The feedback control takes the sensed

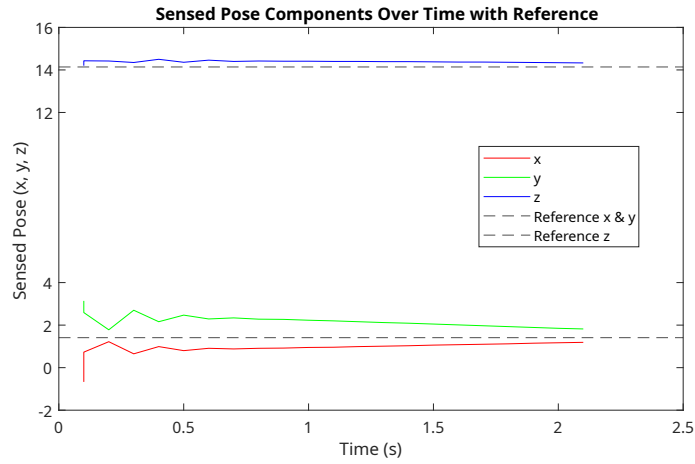


Figure 14: Simulated closed-loop waypoint PID controller showing exponential stability in the presence of modeled mechanical slop.

error from the state in inertial space and using a PID controller, declares a new waypoint to move in space. The satisfaction criteria of the controller is done by minimizing the 2-Norm of the error vector to a total error of .5. Results of the controller in effect shown in Figure 14.

All of the work on the canfield up to this point has been in an effort to control the X-Y-Z position in space of the end effector, however as stated in the beginning, this is a 6 DoF emulation platform with the planar degrees of freedom addressed with the BTV. This would require that the Canfield Joint actuate freely in Roll-Pitch-Heave (RPH). As it turns out a spherical coordinate transformation of the Cartesian workspace is not well defined for the Canfield Joint due to kinematic constraints and the bounded workspace. In the desired variables the bounded workspace of the canfield joint is ± 20 deg for pitch and roll and $\pm 5''$ from the middle of the workspace. To illustrate the issue with a spherical coordinate transformation to change the variables from X-Y-Z to RPH consider the following equations and test case.

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} \cos \theta & \sin \phi \sin \theta & \cos \phi \sin \theta \\ 0 & \cos \phi & -\sin \phi \\ -\sin \theta & \sin \phi \cos \theta & \cos \phi \cos \theta \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ \rho \end{bmatrix} \quad (46)$$

The coordinate system is best described by a "body fixed" coordinate system at the centroid of the end effector, where θ represents the pitch angle and ϕ represents the roll angle relative to the inertial frame. One can solve for the set of change of variable equations, and can quickly see that the transformation diverges at small angles and approximates the workspace as a sphere, further containing the workspace. This prompted the visualization of how RPH changes with X-Y-Z in the inverse kinematics, Simulink, and physical model. Each model gave different results and showed how the underlying assumptions and constraints effect workspace.

It is shown in Figures 15, 16, and 17 that roll and pitch can be approximated as linear functions of y and x, respectively. The proposed linear functions were used to map between an RPH waypoint to the positional inverse kinematics, effectively being used as a transfer function between desired state error and base control inputs.

The full workflow of controlling the Canfield Joint is as follows; Determine Roll Pitch and Heave

waypoint trajectory relative to the BTV coordinate frame. Use empirical mapping of RPH to XYZ to call the inverse kinematics to find the required base joint angles. Solve the 4 Bar closed loop kinematic equations to solve for the required servo angle based on the base joint angles. Actuate the servos and sense the inertial Roll Pitch and Heave of the Canfield end effector frame. Update waypoint until 2-Norm of the error is satisfied.

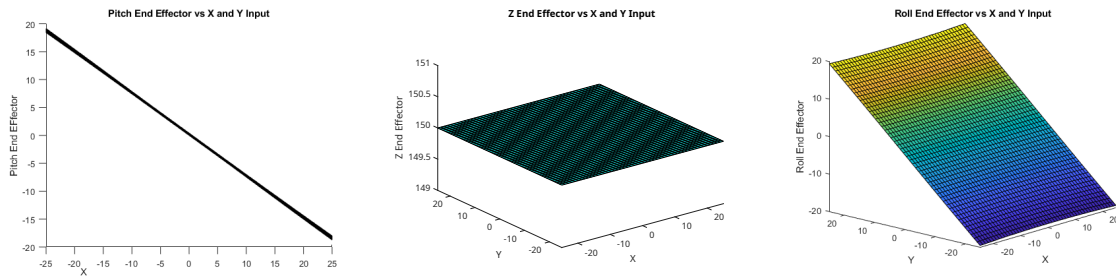


Figure 15: Using the Inverse Kinematics to model: Pitch Heave and Roll vs X-Y workspace. It can be shown that Pitch and Roll are independent linear functions of X and Y, respectively and Heave is independent of X and Y.

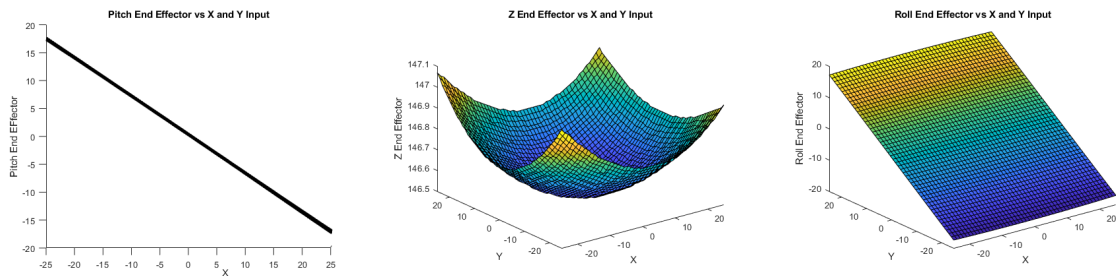


Figure 16: Using Simulink to model the Inverse Kinematics to visualize: Pitch Heave and Roll vs X-Y workspace. It can also be shown that Pitch and Roll are independent linear functions of X and Y, respectively. The Simulink model of the Canfield Joint shows small deviations of the heave axis as X and Y are changing, the order of magnitude of these changes are on the scale of a few mm.

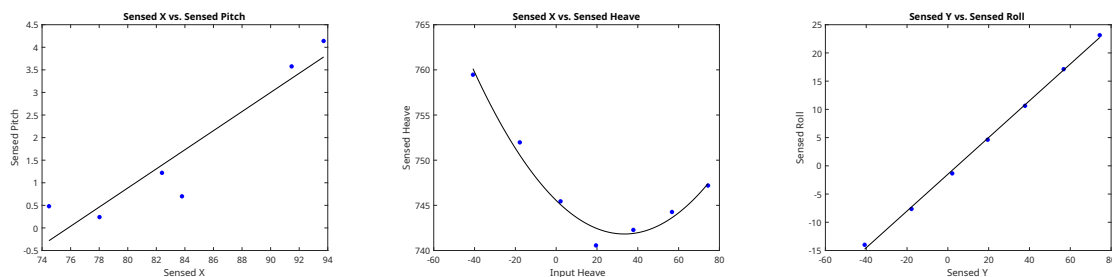


Figure 17: Physical model testing: Pitch Heave and Roll vs X-Y workspace. The physical model agrees with the prediction of the Simulink model

RESULTS

A few Example cases were developed to test the motion emulation capabilities of the system.

Orbit Example The System tracks a circle around the origin with its body x axis pointing towards the origin.

Square Example The BTV tracks a square around the origin with its body axis matching the inertial axis.

Canfield Pointing Example The BTV tracks a circle around the origin with its body axis matching the inertial axis. The Canfield joint tracks a point above the origin.

These examples were produced by a predefined trajectory that was published as a ROS2 tf2 transform. Pose feedback was provided by the Lab's Vicon system. The orbit and square examples show the capabilities of the BTV while the Canfield pointing example showcases the abilities of the whole system.

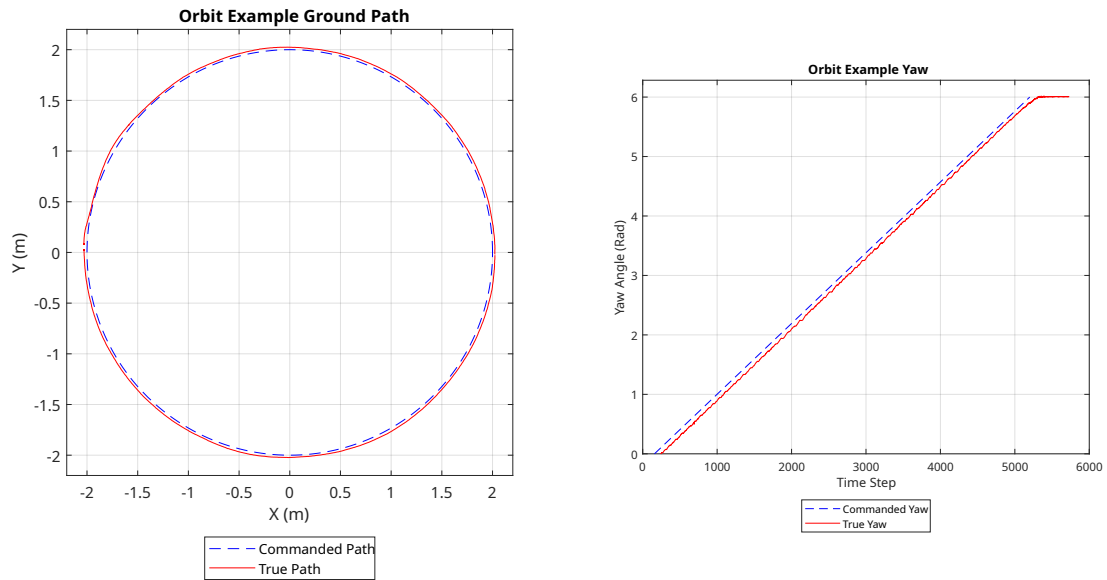


Figure 18: Orbit Example

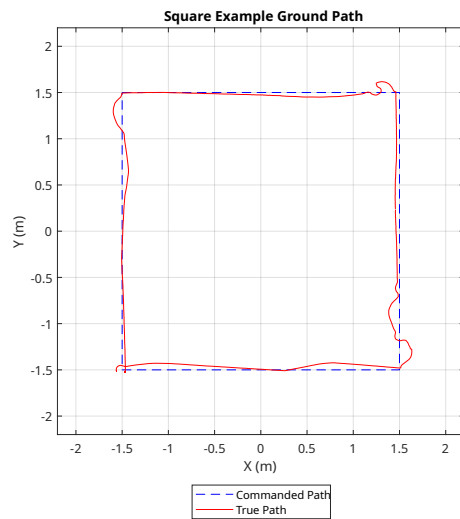


Figure 19: Square Ground Path

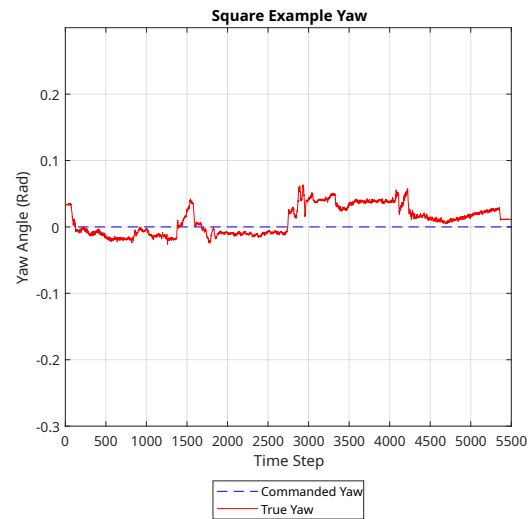


Figure 20: Square Yaw

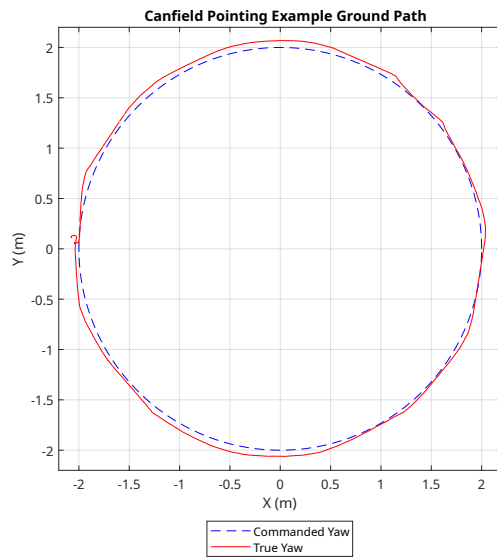


Figure 21: Pointing Ground Path

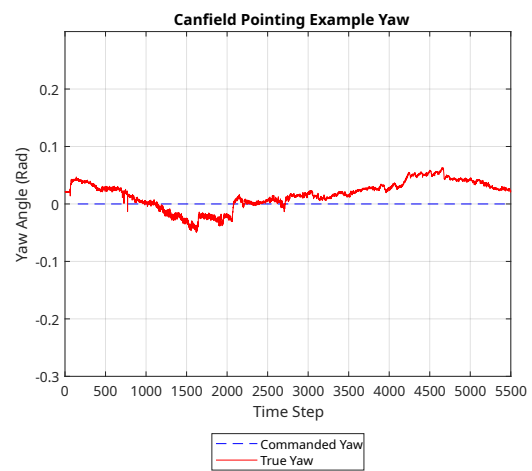


Figure 22: Pointing Yaw

The BTV excels at smooth trajectories such as the one seen in the orbit example. However as can be seen in the square example it struggles with sharp corners. This is partly due to the assumptions used when implementing the caster dynamics and improvement is expected in future work.

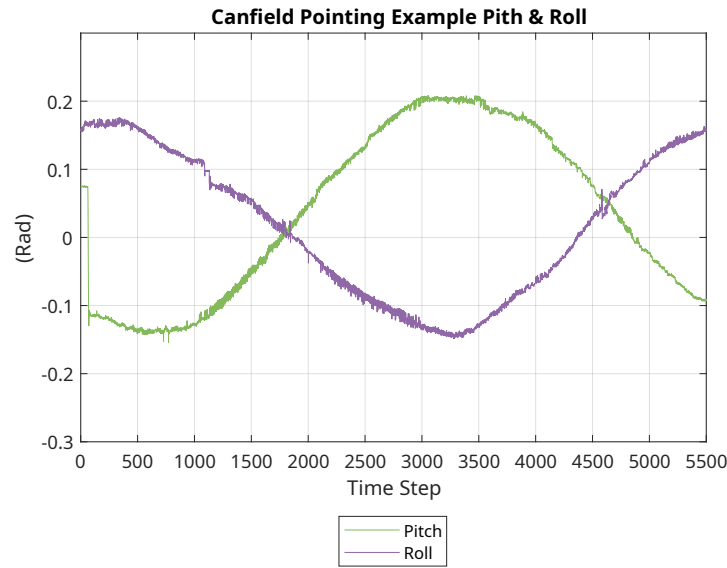


Figure 23: Pointing Pitch and Roll

CONCLUSION

The tracking error produced by the CHOMER system is within the expected ranges. Thus, the system fulfills the goal of being an indeterminate motion emulation platform. Allowing for 6-DOF motion emulation without the large overhead of float-craft or air bearings. It is created with Commercial Off the Shelf (COTS) and 3D printed parts, making it feasible for smaller labs and organizations to construct their own.

Future Work

Further development into the Canfield joint is in progress to increase its workspace, accuracy, and payload. The development of a ground station user interface to streamline the use of the CHOMER System in experiments is underway. Lastly, development of a feedback linearization controller is planned to improve the body-to-motor mapping of the BTV and improve its performance when making sharp movements.

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